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COMMUNICATIONS IN SOIL SCIENCE AND PLANT ANALYSIS
Vol. 35, Nos. 3 & 4, pp. 505–516, 2004

Detecting Nitrogen and Phosphorus Stress in Corn Using Multi-spectral Imagery

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ABSTRACT

The ability to evaluate in-season nutrient deficiencies and/or estimate grain yield could be beneficial to producers in helping make various management decisions. Proper nutrient management decisions could lead to decreased environmental pollution due to over fertilization. A field experiment was established to evaluate the use of multi-spectral imagery for estimating in-season plant biomass, plant nitrogen (N) and phosphorus (P) concentration, grain yield, and grain N and P concentration with varying degree of N and P nutrition. The experiment was a randomized complete block design with four

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DOI: 10.1081/CSS-120029728
0010-3624 (Print); 1532-2416 (Online)
www.dekker.com

replications using a factorial arrangement of treatments in an irrigated continuous corn (*Zea may* L.) system. There were four N rates (0, 67, 134, and 269 $kg\,N\,ha^{-1}$) and four P rates (0, 22, 45, 67 $kg\,P\,ha^{-1}$). Multi-spectral imagery was collected throughout the growing season using a four [blue, green, red, and near-infrared (NIR)]-band sensor. Grain yield, in-season biomass and N concentration increased with increasing N rate for all sampling dates. Biomass production differences due to P deficiency were present only for the early (June) sampling dates. The 1998 imagery had higher regression correlation for in-season biophysical characteristics and grain yield compared to the 1997 growing season, due to differences in sensor sensitivity and increased plant response to applied nutrients. The normalized difference greenness vegetation index (GNDVI) generally had the highest r^2 with grain yield. This study demonstrated the utility of multi-spectral imagery for estimating grain production and nutrient deficiency this could help producers with in-season management decisions.

INTRODUCTION

Precision agriculture might be defined as assessing and understanding the spatial and temporal variability within a field and applying management decisions based on this variability. Spatial variability in soils has always existed for many different reasons; including soil types, landscape positions, past management practices, or other factors.[1] This variability could lead to nonuniform yields and/or uneven yield potential, resulting in areas of the field that should be managed differently for economical or environmental reasons. In the past, management has frequently been based on average conditions for each particular field or for the needs of the most limiting area, resulting in some areas receiving more or less input than needed for optimum yield. These practices contribute to increased environmental pollution due to over-fertilization and/or increased leaching and runoff of nutrients. Site-specific management has recently received attention as a technology that has the potential to explain and overcome some of the spatial variability problems within fields. Tools now exist to help identify and manage different spatial zones according to the best management practice for each area, thereby decreasing the potential for environmental pollution.

Researchers initially investigated the potential for using grid soil sampling, to make variable rate nutrient recommendations, but this approach proved to be extremely costly, labor intensive and time consuming. An alternative method for assessing spatial variability is remote sensing. Remote sensing may be defined as the process of obtaining information about an object, area, or phenomenon by analyzing data acquired from a device that is not in contact with the object, area, or phenomenon.[2] There are a number of different ways to obtain remotely sensed data including; aerial photography, satellite images, hand held radiometers, or aircraft mounted sensors. One of the first agricultural applications of remote sensing used aerial photography to assist with soil mapping in the early 1920's. Other applications in agriculture include crop identification, yield forecasting, rangeland surveys, and monitoring initial crop conditions for insect and/or disease pressures.[3]

Some of the more recent studies have used hyper-spectral imagery to determine which particular wavelength or combination of wavelengths are indicative of a particular nutrient deficiency or stress factor. Reflectance in the green region of the visible portion of the electromagnetic spectrum is a good indicator of N content in crops including; corn, wheat, and bermudagrass.[4–7] Milton et al.[8] grew soybean plants in hydroponic solution at three P concentrations and measured weekly changes in leaf spectral reflectance. They found that P deficient plants had a higher reflectance in the green and yellow portion of the spectrum and did not show the normal shift of the red edge (chlorophyll absorption band 680 nm).

One of the more common techniques uses multi-spectral imagery to detect or estimate various vegetative parameters including; biomass, leaf area index, nutrient deficiencies, water stress, weed pressures, emergence date, and yield. Using hand-held or vehicle mounted hyper-spectral systems to measure reflectance; researchers have collected reflectance data corresponding to similar wavebands available in various satellite-sensed data an example include work by Kleman and Fagerlund,[9] who investigated wavebands that are present on the Landsat multi-spectral scanner (MSS), by using a radiometer measuring 400–2300 nm. They found that a NIR (800 nm) to red (680 nm) ratio was highly correlated to total biomass in the early growth stages for barley. A reflectance ratio of 800:1650 nm was better for biomass estimation at later growth stages and grain yield. Ahlrichs and Bauer[10] found that variation in reflectance in the NIR band best explained leaf area index and percent soil cover while reflectance in the mid-infrared band explained differences in fresh biomass, dry biomass, and water content.

Many researchers have investigated the relationship between wavelength combinations (indexes) or reflectance at particular wavelengths with various vegetation parameters using satellite or aerial based systems, but few have collected intense ground truthing information to verify relationships. The normalized difference vegetation index (NDVI) developed by Tucker[11] is most widely used index. The NDVI is correlated with a number of different vegetation parameters such as green leaf area, biomass, and percent ground cover.[12,13] Additional research to verify remotely sensed imagery with intense ground truthing is needed. Therefore the objective of this work was to evaluate the use of multispectral imagery for estimating in-season plant biomass, plant N and P concentration, grain yield, and grain N and P concentration with varying degree of N and P nutrition.

MATERIALS AND METHODS

A continuous irrigated corn (*Zea mays* L.) experiment was conducted on a Hord silt loam (fine-silty, mixed, mesic Cumulic Haplustolls) located at the Management Systems Evaluation Area (MSEA) project near Shelton, NE. A linear drive irrigation system was used in a conventional tillage system with disking occurring late April and cultivation in mid June at approximately V5 growth stage. Total irrigation amounts were 200.8 mm during 1997 and 115.2 mm during 1998. Growing conditions during 1997 and 1998 were similar with respect to average daily temperature and growing degree days, but rainfall amount was different between the two years with 247 mm for 1997 compared to 457 mm in the 1998 season. The seeding rate was 74,000 plants ha^{-1} with Pioneer brand hybrid 3225 planted on 1 May 1997 and 4 May 1998. Initial surface soil test characteristics indicated a soil pH of 6.5, organic matter level of 1.8%, residual soil nitrate at 21.5, P at 7.0 and potassium at 493 mg kg^{-1}. The experimental design was a randomized complete block design with four replications. The treatment design was a four by four-factorial arrangement. Nitrogen was applied as NH_4NO_3 in a split application with ½ applied preplant and the remaining ½ sidedressed at V5–V6 growth stage. Total N rates consisted of 0, 67, 134, and 269 kg N ha^{-1}. Phosphorus was applied preplant and incorporated as triple superphosphate at rates of 0, 22, 45, and 67 kg P ha^{-1}. Plot size was 9.14 × 15.24 m with 0.76 m row spacing. "Guardsman" [Dimethenamid (2-chloro-N-[(1-methyl-2-methoxy)ethyl]-N-(2,4-dimethyl-thien-3-yl)-acetamide] + Atrazine(2-chloro-4-ethylamino-6-isopropyl-amino-s-trazine)] 53.1% active ingredient were applied to all plots at a rate of 3.5 L ha^{-1} in early May. Phenology data according to Ritchie et al.[14] were recorded weekly from the first of June until the end of August and then bi-weekly until maturity.

Biomass sampling was performed throughout the growing season by taking 12 randomly selected plants from the east quarter of the plots.

Whole plants were weighed and ears were separated once distinguishable. Whole plants were chopped with a chipper-shredder in the field to facilitate subsampling. Subsamples were weighed, oven dried at 50°C, and then reweighed for water content. All samples were ground with a Wiley Mill to pass a 2 mm sieve. Nitrogen concentration was determined on all samples using dry combustion[15] and total P was determined using energy dispersive X-ray fluorescence.[16] Grain yield was estimated by hand harvesting 3.05 m from each of the four middle rows. Ears were shelled and water content determined. Grain samples were oven dried at 50°C, ground, and analyzed as described above for biomass samples. Grain yield per plot was calculated and corrected to $155\,g\,kg^{-1}$ moisture.

Multi-spectral airborne imagery, consisting of four bands; blue (485 ± 35), green (550 ± 35), red (660 ± 30), and NIR (830 ± 70) was collected on various dates throughout the growing season. Images were obtained on cloud-free days at about solar noon, downloaded and rectified to a 1 m pixel resolution. The sensor used in the 1997 growing season was a 8-bit system, while the sensor for the 1998 growing season was a 12-bit system. Therefore the 1998 system was 16 times more sensitive compared to the 1997 system. Four $64\,m^2$ calibration tarps of known reflectance characteristic for each band were visible in each image. Imagery was converted to percent reflectance for each band using the calibration tarps and various indexed calculations. Pixel values were averaged to obtain an average reflectance value for each plot. Normalized difference vegetation index (NDVI) [(NIR − red)/(NIR + red)], and normalized difference greenness vegetation index (GNDVI) [(NIR − green)/(NIR + green)] were calculated for each plot.

Least significant difference (LSD) tests were performed on all plant biomass, plant N concentration, grain yield and grain N concentration using the GLM procedure in SAS.[17] Linear regression was utilized to develop regression for plant measurements with individual waveband and indexes using the REG procedure in SAS.[17]

RESULTS AND DISCUSSION

In-Season Biomass and Grain Harvest

Mean separation by treatment for in-season biomass, plant N and P concentrations, grain yield and grain N and P concentrations are reported in Tables 1 and 2. In general, grain yield, plant biomass, grain N concentration, and plant N concentration increased with increasing N rate for all sampling dates and years (Tables 1 and 2). Applied P affected

Table 1. In-season plant biomass treatment means, and mean separation for biomass production, N, and P concentration by sampling date, Shelton, NE, 1997 and 1998.

	Biomass ($Mg\,ha^{-1}$)		N ($g\,kg^{-1}$)		P ($g\,kg^{-1}$)	
N Rate ($kg\,ha^{-1}$)			1997			
	20 June	15 July	20 June	15 July	20 June	15 July
0	0.61 b[a]	4.02 c	2.83 c	1.45 c	0.271 a	0.228 b
67	0.63 b	4.72 b	3.30 b	1.75 b	0.251 b	0.246 ba
134	0.71 a	5.37 ab	3.33 b	1.94 a	0.258 b	0.250 a
269	0.77 a	5.08 a	3.56 a	1.97 a	0.261 ab	0.254 a
P Rate ($kg\,ha^{-1}$)						
0	0.57 c	4.52 a	3.40 a	1.85 a	0.264 a	0.228 b
22	0.67 b	4.71 a	3.23 ab	1.81 ba	0.249 b	0.258 a
45	0.76 a	4.93 a	3.20 b	1.74 b	0.262 a	0.245 ab
67	0.72 ab	5.04 a	3.19 b	1.72 b	0.267 a	0.247 ab
N Rate ($kg\,ha^{-1}$)			1998			
	19 June	20 July	19 June	20 July	19 June	20 July
0	0.28 c	7.38 c	1.99 bc	0.84 c	0.401 a	0.281 a
67	0.59 b	11.20 b	1.94 c	1.05 b	0.292 b	0.227 b
134	0.68 b	12.31 b	2.13 b	1.16 b	0.255 b	0.198 c
269	0.93 a	15.13 a	2.73 a	1.44 a	0.276 b	0.209 bc
P Rate ($kg\,ha^{-1}$)						
0	0.47 b	10.66 a	2.37 a	1.15 a	0.297 ab	0.208 b
22	0.64 a	11.67 a	2.24 ab	1.14 a	0.281 b	0.222 b
45	0.69 a	12.27 a	2.12 bc	1.13 a	0.319 ab	0.229 ab
67	0.67 a	11.42 a	2.05 c	1.08 a	0.327 a	0.256 a

[a]Values in each category followed by the same letter are not significantly different at the 0.05 probability level according to a protected LSD test.

biomass only for the late June sampling in 1997 and 1998 (Table 1). Although biomass production increased with increasing N rate for the second growing season, increasing N rate decreased P content. Plots receiving no N had a higher P content compared to the N fertilized plots for all sampling dates, possibly due to dilution from the reduction in growth from an N deficiency. Grain yield response to applied P was only observed between the 0 and 22 $kg\,P\,ha^{-1}$ rates, with the three higher rates having a similar response in 1997 while grain yield were similar for all P rates in 1998 (Table 2). Increased response to applied N for 1998 compared to 1997 was illustrated by differences in grain yield. Yield increased by 29% in 1997 and 92% in 1998 for the 67 $kg\,N\,ha^{-1}$ rate over the 0 $kg\,N\,ha^{-1}$ rate, with no significant difference in yield between

Table 2. Grain yield and grain N and P concentration by main treatment effects and corresponding mean separations, Shelton, NE, 1997 and 1998.

	Grain yield (Mg ha^{-1})		N (g kg^{-1})		P (g kg^{-1})	
	1997	1998	1997	1998	1997	1998
N Rate (kg ha^{-1})						
0	9.13 b	3.30 d	1.05 b	0.91 c	0.410 a	0.191 b
67	11.73 a	6.33 c	1.09 b	0.88 c	0.403 a	0.186 b
134	11.98 a	8.55 b	1.20 a	0.99 b	0.377 a	0.184 b
269	11.88 a	10.25 a	1.21 a	1.19 a	0.390 a	0.204 a
P Rate (kg ha^{-1})						
0	10.30 b	6.93 a	1.16 a	0.97 a	0.389 a	0.167 b
22	11.38 a	7.05 a	1.12 a	1.00 a	0.381 a	0.204 a
45	11.53 a	7.20 a	1.12 a	1.00 a	0.394 a	0.196 a
67	11.50 a	7.25 a	1.15 a	1.00 a	0.415 a	0.198 a

[a]Values in each category followed by the same letter are not significantly different at the 0.05 probability level according to a protected LSD test.

the 134 and 269 kg N ha^{-1} rates in 1997. In 1998 the greatest yield was for the 269 kg N ha^{-1} rate that was significantly higher than the other N treatments.

In-Season Biomass Image Analysis

Analysis of multi-spectral images and plant measurements were performed on plant sampling within ±2 days of image collection. Overall the 1998 imagery resulted in a better ability to predict in-season biophysical characteristics for each experiment compared to the 1997 growing season (Table 3). This difference could be attributed in part to the differences in sensor sensitivity, the sensor used in the 1998 season was 16 times more sensitive compared to the sensor utilized in 1997. Increased response to applied nutrient as illustrated by differences in biomass production for 1998 compared to 1997 could also be a factor contributing to the 1998 imagery having higher regression correlations (Tables 1 and 3). Although there were significant correlations with biomass for 1997, there were none greater than 0.50. Correlation with biomass production was higher for the June sampling compared to the July sampling during the 1998 growing season for all of the bands (except green) and indices (Table 3). The plants were tasseling at the July

Table 3. Linear regression correlation (r^2) for biomass sampling, plant N and P concentration with individual waveband and vegetation index by biomass sampling date and corresponding growth stage, Shelton, NE, 1997 and 1998.

	20 June 1997 (V6)[c]	15 July 1997 (V14–VT)	19 June 1998 (V5–V7)	20 July 1998 (V14–R1)
		Blue		
Biomass ($\mathrm{Mg\,ha^{-1}}$)	0.18[a]	0.25[a]	0.60[a]	0.24[a]
Plant N ($\mathrm{g\,kg^{-1}}$)	0.00	0.22[a]	0.00	0.35[a]
Plant P ($\mathrm{g\,kg^{-1}}$)	0.01	0.04	0.14[a]	0.06[b]
		Green		
Biomass ($\mathrm{Mg\,ha^{-1}}$)	0.45[a]	0.27[a]	0.18[a]	0.40[a]
Plant N ($\mathrm{g\,kg^{-1}}$)	0.01	0.41[a]	0.01	0.48[a]
Plant P ($\mathrm{g\,kg^{-1}}$)	0.00	0.10[b]	0.01	0.16[a]
		Red		
Biomass ($\mathrm{Mg\,ha^{-1}}$)	0.01	0.27[a]	0.48[a]	0.37[a]
Plant N ($\mathrm{g\,kg^{-1}}$)	0.00	0.34[a]	0.00	0.45[a]
Plant P ($\mathrm{g\,kg^{-1}}$)	0.00	0.05[b]	0.09[b]	0.14[a]
		NIR		
Biomass ($\mathrm{Mg\,ha^{-1}}$)	0.36[a]	0.11[a]	0.56[a]	0.27[a]
Plant N ($\mathrm{g\,kg^{-1}}$)	0.02	0.27[a]	0.11[a]	0.25[a]
Plant P ($\mathrm{g\,kg^{-1}}$)	0.00	0.05	0.29[a]	0.40[a]
		NDVI		
Biomass ($\mathrm{Mg\,ha^{-1}}$)	0.01	0.24[a]	0.63[a]	0.45[a]
Plant N ($\mathrm{g\,kg^{-1}}$)	0.00	0.38[a]	0.04	0.52[a]
Plant P ($\mathrm{g\,kg^{-1}}$)	0.00	0.06	0.26[a]	0.26[a]
		GNDVI		
Biomass ($\mathrm{Mg\,ha^{-1}}$)	0.48[a]	0.27[a]	0.69[a]	0.50[a]
Plant N ($\mathrm{g\,kg^{-1}}$)	0.02	0.47[a]	0.07[b]	0.53[a]
Plant P ($\mathrm{g\,kg^{-1}}$)	0.00	0.10[a]	0.26[a]	0.36[a]

[a,b]—significant at the 0.01 and 0.05 probability levels, respectively.
[c]—plant growth stage according to Ritchie et al.[14]

sampling date, which could have influenced the imagery thus decreasing correlations. Regardless of year the July sampling dates had a higher correlation with plant N concentration compared to the early dates. Imagery analysis with plant P concentration never exceeded 0.40 although there were a few significant correlations in 1998. The highest correlations were for the late sampling in 1998. Overall the GNDVI index had the higher correlation for biomass production and plant N concentration, while the NIR waveband had the highest correlation with plant P concentration (Table 3).

Grain Yield Image Analysis

Grain yield and nutrient analysis of multi-spectral images were performed for all image collection dates beginning in late June and continuing until late August with four sampling dates for each year extending from the vegetative through the reproductive growth stages. Similar to the in-season biomass analysis, the 1998 imagery resulted in better correlations with grain yield and nutrient concentrations compared to the 1997 growing season, again possibly due in part to greater image sensitivity, but also due to the increased response to applied N as indicated by grain yield data (Tables 2 and 4). Generally the late June sampling date had the lowest correlation compared to later sampling dates for each experiment regardless of waveband or index. Plant growth stage at this image sampling date was done between V5–V7 depending on experiment and treatment. At this growth stage there was a significant amount of soil reflectance present within each pixel. This could have contributed to the lower correlation compared to the later sampling date when the canopy was closed and the soil background was no longer present. This sampling date for the 1998 imagery was the only imagery significantly correlated with grain P concentration (Table 4). This image collection date corresponded to the June biomass sampling date which was the only date exhibiting and increase in biomass production due to P application (Table 1). Similar to previous research the green waveband had the best correlation with grain N concentration. Blackmer et al.[6] stated that light reflectance near 550 nm (green) was best for separating N treatment differences, and could be used to detect N deficiencies in corn. The GNDVI index had the best correlation with grain yield; this is similar to recent results of Shanahan et al.,[18] who found that the GNDVI index obtained during midgrain field has the greatest potential of estimating grain yield.

CONCLUSIONS

Grain yield, plant biomass, grain N concentration, and plant N concentration were all affected by N rate. Grain yield response to P was only present in 1997. Overall, the 1998 imagery resulted in higher regression correlation for in-season biophysical characteristics and grain yield compared to the 1997 growing season. This difference was attributed in part to the differences in sensor sensitivity, but also differences in plant response to applied nutrients. Correlations with grain yield and biomass

Table 4. Linear regression correlation (r^2) for grain yield, grain N, and P concentration with individual waveband and vegetation index by image collection date and corresponding growth stage, Shelton, NE, 1997 and 1998.

	1997				1998			
	20 June (V6)^{c}	15 July (V14–VT)	7 Aug (R2)	17 Aug (R4)	19 June (V5–V7)	17 July (V14–R1)	6 Aug (R2–R3)	19 Aug (R4–R5)
					Blue			
Yield (Mg ha^{-1})	0.31^{b}	0.31^{b}	0.00	0.03	0.48^{b}	0.70^{b}	0.48^{b}	0.43^{b}
N (g kg^{-1})	0.05	0.07^{a}	0.02	0.03	0.25^{b}	0.22^{b}	0.29^{b}	0.32^{b}
P (g kg^{-1})	0.00	0.00	0.00	0.01	0.12^{b}	0.00	0.07^{a}	0.02
					Green			
Yield (Mg ha^{-1})	0.49^{b}	0.69^{b}	0.65^{b}	0.65^{b}	0.06	0.78^{b}	0.68^{b}	0.76^{b}
N (g kg^{-1})	0.05	0.13^{b}	0.24^{b}	0.23^{b}	0.04	0.29^{b}	0.41v	0.53^{b}
P (g kg^{-1})	0.00	0.01	0.00	0.01	0.10^{a}	0.00	0.05	0.03
					Red			
Yield (Mg ha^{-1})	0.00	0.44^{b}	0.45^{b}	0.43^{b}	0.35^{b}	0.71^{b}	0.64^{b}	0.68^{b}
N (g kg^{-1})	0.07^{a}	0.20^{b}	0.17^{b}	0.22^{b}	0.17^{b}	0.22^{b}	0.32^{b}	0.40^{b}
P (g kg^{-1})	0.02	0.02	0.00	0.02	0.11^{b}	0.00	0.04	0.02
					NIR			
Yield (Mg ha^{-1})	0.26^{b}	0.29^{b}	0.10^{b}	0.05	0.68^{b}	0.39v	0.47^{b}	0.65^{b}
N (g kg^{-1})	0.06	0.27^{b}	0.01	0.09^{a}	0.43^{b}	0.18^{b}	0.21^{b}	0.37^{b}
P (g kg^{-1})	0.02	0.03	0.05	0.04	0.05	0.01	0.02	0.01
					NDVI			
Yield (Mg ha^{-1})	0.01	0.47^{b}	0.49^{b}	0.34^{b}	0.64^{b}	0.74^{b}	0.79^{b}	0.74^{b}
N (g kg^{-1})	0.10^{a}	0.27^{b}	0.15^{b}	0.21^{b}	0.34^{b}	0.25^{b}	0.36^{b}	0.40^{b}
P (g kg^{-1})	0.03	0.00	0.01	0.03	0.08^{a}	0.00	0.01	0.02
					GNDVI			
Yield (Mg ha^{-1})	0.47^{b}	0.69^{b}	0.66^{b}	0.59^{b}	0.71^{b}	0.81^{b}	0.87^{b}	0.82^{b}
N (g kg^{-1})	0.06^{a}	0.23^{b}	0.21^{b}	0.24^{b}	0.40^{b}	0.31^{b}	0.44^{b}	0.50^{b}
P (g kg^{-1})	0.01	0.00	0.01	0.02	0.08^{a}	0.00	0.01	0.02

^{a,b}—significant at the 0.05 and 0.01 probability levels, respectively.
^{c}—plant growth stage according to Ritchie et al.[14]

were better later in the growing season, once the crop canopy had closed (the late vegetative to reproductive growth stages). Generally the GNDVI had the greatest correlation with grain yield. Acceptance of precision agriculture as a viable management decision tool is dependent on its ability to accurately assess a given variable regardless of other factors including various nutrient deficiencies, and/or the presence of pest pressures including weed, insect, or disease. The ability of remotely sensed imagery to accurately estimate grain yield regardless of N, and/or P deficiency was demonstrated by the highly significant correlation of the GNDVI index with grain yield in the presences of N, and/or P deficiency.

REFERENCES

1. Kincheloe, S. Tools to aid management: the use of site specific management. J. Soil Water Conser. **1994**, *49*, 43–45.
2. Lillesand, T.M.; Kiefer, R.W. *Remote Sensing and Image Interpretation*, 2nd Ed.; John Wiley & Sons, Inc.: New York, 1987.
3. Bauer, M.E. The role of remote sensing in determining the distribution of yield of crops. Adv. Agron. **1975**, *27*, 271–304.
4. Walburg, G.; Bauer, M.E.; Daughtry, C.S.T.; Housley, T.L. Effects of nitrogen nutrition on the growth, yield, and reflectance characteristics of corn canopies. Agron. J. **1982**, *74*, 677–683.
5. Aase, J.K.; Tanaka, D.L. Effects of tillage practices on soil and wheat spectral reflectance. Agron. J. **1984**, *76*, 814–818.
6. Blackmer, T.M.; Schepers, J.S.; Varvel, G.E. Light reflectance compared with other nitrogen stress measurement in corn leaves. Agron. J. **1994**, *86*, 934–938.
7. Blackmer, T.M.; Schepers, J.S.; Varvel, G.E.; Walter-Shea, E.A. Nitrogen deficiency detection using reflected shortwave radiation from irrigated corn canopies. Agron. J. **1996**, *88*, 1–5.
8. Milton, N.M.; Eiswerth, B.A.; Ager, C.M. Effect of phosphorus deficiency on spectral reflectance and morphology of soybean plants. Remote Sens. Environ. **1991**, *36*, 121–127.
9. Kleman, J.; Fagerlund, E. Influence of different nitrogen and irrigation treatments on the spectral reflectance of barley. Remote Sens. Environ. **1987**, *21*, 1–14.
10. Ahlrichs, J.S.; Bauer, M.E. Relation of agronomic and multispectral reflectance characteristics of spring wheat canopies. Agron. J. **1983**, *75*, 987–993.
11. Tucker, C.J. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens. Environ. **1979**, *8*, 127–150.
12. Asrar, G.; Fuchs, M.; Kanemasu, E.T.; Hatfield, J.L. Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat. Agron. J. **1984**, *76*, 300–306.
13. Ma, B.L.; Morrison, M.J.; Dwyer, L.M. Canopy light reflectance and field greenness to assess nitrogen fertilization and yield of maize. Agron. J. **1996**, *88*, 915–920.

14. Ritchie, S.W.; Hanway, J.J.; Benson, G.O. *How a Corn Plants Develops*; Iowa State Univ. of Sci. and Tech. Coop. Ext. Service: Ames, IA, 1997; Spec. Pub. 48.
15. Schepers, J.S.; Francis, D.D.; Tompson, M.T. Simultaneous determination of total C, total N and ^{15}N on soil and plant material. Commun. Soil Sci. Plant Anal. **1989**, *20*, 949–959.
16. Knudsen, D.; Clark, R.B.; Denning, J.L.; Pier, P.A. Plant analysis of trace elements by x-ray. J. Plant Nutr. **1981**, *3*, 61–75.
17. SAS Institute. In *SAS/STAT Procedures*; Release 6.03, Ed.; SAS Inst.: Cary, NC, 1988.
18. Shanahan, J.F.; Schepers, J.S.; Francis, D.D.; Varvel, G.E.; Wilhelm, W.W.; Tringe, J.M.; Schlemmer, M.R.; Major, D.J. Use of remote-sensing imagery to estimate corn grain yield. Agron. J. **2001**, *93*, 583–589.